Tunable whispering gallery modes for spectroscopy and CQED experiments

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Abstract. We have tuned the whispering gallery modes of a fused silica micro-resonator over nearly 1 nm at 800 nm, i.e. over half of a free spectral range or the equivalent of 10^6 linewidths of the resonator. This has been achieved by a new method based on the stretching of a two-stem microsphere. The devices described below will permit new Cavity-QED experiments with this ultra high finesse optical resonator when it is desirable to optimise its coupling to emitters with given transition frequencies. The tuning capability demonstrated is compatible with both UHV and low temperature operation, which should be useful for future experiments with laser cooled atoms or single quantum dots. A general overview of the current state of the art in microspheres is given as well as a more general introduction.

1. Introduction

Optical micro-cavities have attracted much interest in the field of quantum cavity electrodynamics[1, 2] as well as in classical and nonlinear optics[3, 4, 5].

Very low mode-volume semiconductor cavities using multi-layer dielectric mirrors have been developed. Low threshold lasing [6, 7] and cavity enhanced spontaneous emission [8, 9] have been observed. Small Fabry Perot cavities have a larger mode-volume but can achieve very high quality factors ($Q = \nu/\Delta\nu$). The strong coupling regime has been reached between single alkali atoms and the fundamental mode of the cavity [10, 11]. The resulting Rabi-splitting of the coupled mode [12], as well as the single atom laser action [13] have been demonstrated. More recently an atom has been trapped by a single photon in such a cavity and its motion deduced from the optical signature.[11, 14]

An attractive alternative to Fabry Perot cavities are solid dielectric microspheres having at the same time a very low modevolume *and* very high quality factors. Light can be trapped in so called whispering gallery modes (WGMs) if the refractive index of the material of the sphere is larger than the one surrounding it.‡ Successive total internal reflections off the concave inner surface confine the light into a thin ring close to the equator. These high-Q ring modes have been observed and studied extensively in droplets.[16] It was soon recognised that the field enhancement caused by the strong confinement of the light in these modes combined with their high quality factors could lead to strong Cavity QED effects. Stimulated Raman scattering, to name but one, has been observed in small CS_2 droplets with a threshold of just three photons per mode.[5] Whispering-gallery modes have also been used to produce lasers in microdisks[17] and to enhance the spontaneous emission of quantum dots in micropillar stuctures[18].

However, semiconductor microdisks and pillars can only operate in the low-Q regime and microdroplets suffer unfortunately from evaporation and gravitational pull. This problem has been overcome in the pioneering work of V Braginsky et al. [19]. He and his coworkers realised that whispering-gallery modes in silica micropsheres unique combination of small mode resonators with ultra high Q factors. Moreover, these spheres remain attached to a thin stem of silica and thus are easily manipulated and are easily produced in the laboratory. For microspheres ($\varnothing \simeq 40\,\mu$m) the modevolume can be exceedingly small ($V \sim 100\,\mu\mathrm{m}^3$). The electrical field for a *single photon* in such a mode is of the order of 10 kV/m. At the same time the quality factor of, e.g. silica microspheres, can be as high as 10^{10} with photon storage times of the order of one microsecond.[20, 21] Clearly such a system is ideally suited for the observation of nonlinear optical effects and CavityQED experiments.

‡ WGMs had first been observed in the gallery of the cupola of St.Paul's Cathedral in London. A whisper spoken close to the wall can be heard all the way along the gallery, some 42 m to the other side. Lord Rayleigh was the first to identify the refocusing effect of the curved surface as the sound travels along the gallery. He also conjectured the existence of the thus called whispering gallery modes. He also suggested that such modes of the electromagnetic field could find some applications due to the extreme confinement of the field.[15]

2. WHISPERING GALLERY MODES IN MICROSPHERES

This section gives a short overview over the general properties of whispering gallery modes (WGMs). A more detailed account of the theory of the WGMs and on experiments performed on microspheres can be found in References [22, 16].

A transparent dielectric sphere can sustain WGMs if its circumference is larger than a few wavelengths. Figure 1) shows a typical single-stemmed silica microsphere produced in our laboratory. The WGMs can be understood as high angular momentum electromagnetic modes in which light propagates by repeated total internal reflection surface at grazing incidence with the proper phase matching condition. The modes can readily be derived from Maxwell's equations solved in spherical coordinates. The angular dependence of the field is naturally described with spherical harmonics. The two quantum numbers l and m (with $m = -l, \ldots + l$) describe the total angular momentum and its projection upon the reference axes respectively. Quantum numbers m of opposite sign correspond to waves propagating in opposite directions along the perimeter of the sphere. The modes offering the highest polar confinement and thus the smallest modevolume correspond to values $|m|$ close to l. In the radial direction the index discontinuity creates a potential well which combines with the centrifugal barrier to form a pocket like pseudo-potential. This effective potential approach has been analyzed in detail by H M Nussenzveig [23]. It provides good physical insight in many properties of the WGMs which appear as quasibound states of light, analogous to the circular Rydberg states of alkali atoms. The radial confinement of the WGMs is characterized by the quantum number n, the number of antinodes of the field amplitude. The modes with $n = 1$ are the most confined in radial direction both in terms of the modevolume and 'leakage'. In the image of geometrical optics these modes undergo a maximum of reflections at the surface and thus have the smallest reflection angle, the lowest diffraction losses. Modes near this condition have a free spectral range FSR $\cong c/(Nl\lambda)$. The boundary conditions imposed on the field depend on its polarization: Modes with TE and TM polarization will undergo different phase-shifts upon reflection at the surface of the sphere. Two modes which differ only in polarisation will exhibit resonance frequencies a substantial fraction of an FSR apart.

In short, once the polarization of the mode is assigned, WGM's are described by three integers n, l, and m. The mode with the longest life time and the smallest volume is $(l = l_{max}, |m| = \pm l, n = 1)$. It is confined near the bottom of the potential well, i.e. as close as possible to the sphere's surface. It has a maximum angular momentum of $l \simeq Nka \simeq Nx$, with x being the size parameter ($x = ka = 2\pi a/\lambda$) of a sphere of radius a. Its cross section is almost Gaussian both in polar and radial direction.

Light trapped in these modes can escape out of the sphere only by tunnelling across the potential barrier which extends as far as Na for this state. The very short evanescent tail ($\simeq \lambda/2\pi$) of the quasi-bound state ($n \cong 1$) implies a very weak coupling to the outside medium and thus extremely high quality factors $Q = \nu/\Delta\nu$. In highly transparent media such as fused synthetic silica the diffraction losses are negligible

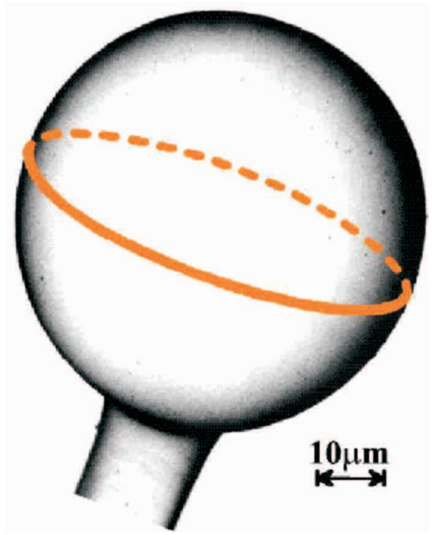

Figure 1. Scanning electronic microscope image of a fused-silica microsphere, 56 microns in diameter.

for spheres larger than $a = 20\,\mu$m. A given Q value is related to an attenuation α by the formula $Q = 2\pi N/(0.23\alpha\lambda)$ where α is expressed in dB/m. The minimum attenuation observed in this wavelength region on silica optical fibres is about 3 dB/km corresponding to $Q = 2\times10^{10}$. Absorption, scattering on impurities, and residual surface roughness limit in praxis the Q to about 3×10^9 at 780 nm[19, 20, 21] corresponding to an attenuation of 17 dB/km.

2.1. Coupling light into whispering gallery modes

The very high diffraction limited Q of the fundamental modes of larger spheres implies that free space coupling to the microspheres is very inefficient. In order to achieve efficient coupling the free space beam has to be matched to the WGM. Close to the surface of the sphere the excitation beam has to have the same shape and angular momentum (with respect to the centre of the sphere) as the mode. The potential barrier created by the index discontinuity at the surface of the sphere confines almost all of the field to the inside of the sphere. However, a short evanescent tail of the electro magnetic field protrudes from the sphere. If a material of high refractive index is brought into this evanescent wave some of the light will tunnel across the gap between the material and the sphere, also known as frustrated total internal reflection. This can be achieved with a prism of high refractive index (Np) almost in contact with the sphere. If an incident beam hits the prism surface with an angle θ close to the critical angle $\theta = \arcsin(N/Np)$ so that its angular momentum with respect to the centre of the sphere is $N_p ka \sin\theta \simeq Nka$ its light can be fed into a WGM. By slightly changing the angle of incidence and the frequency of the beam different WGMs can be selectively

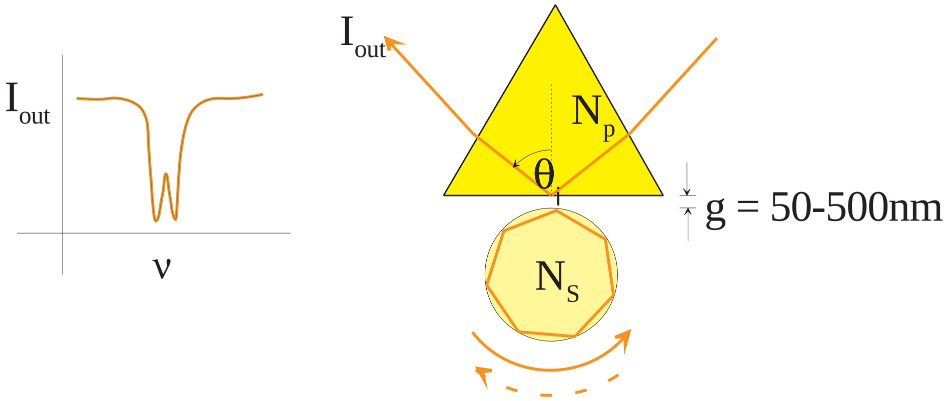

Figure 2. Approaching a high refractive index prism to the sphere (not to scale) one can frustrate the total internal reflection of the WGMs within the sphere and couple light into or out of the sphere.

excited.§ Using the prism coupling scheme efficiencies exceeding 30% can be achieved for various mode geometries. The resonances appear as dips in the intensity of the beam reflected from the prism (figure 2). The depth of these dips is a direct measure of the coupling efficiency. Due to the nature of evanescent waves the coupling rate decreases exponentially with increasing gap size. The ability to control the coupling rates is an important advantage of microspheres as compared to other resonators where the coupling rate is fixed by the reflectivity of the mirrors. The highest coupling efficiency between the free space modes and the WGMs is achieved with a gap of a few hundred nanometres where the coupling rate matches the other losses of the resonator (generally absorption and diffraction by surface the roughness). The intrinsic quality factors of up to 10^{10} can only be measured with very large gaps (typically of the order of 1 μm).

3. Experiments on microspheres in Paris

3.1. Experimental set up

The experiments described here are all based on the prism coupler method: The light is coupled into and out of the sphere via a prism. As described above the incoming beam has to match the whispering gallery mode in frequency, spot size, and angular momentum. It is therefore necessary to have full control over all parameters of the incoming Gaussian beam: frequency, waist diameter and position, and angles of incidence with the prism. Figure 4 shows a schematic of the setup used in the experiments presented here. A photographic image of the coupling lenses and the prism can be seen in figure 3. When narrow linewidth is required, e.g. for a measurement of the ultimate Q a grating stabilised laser was used. A laser diode (Yokogawa YL78XNL) with integrated Bragg grating serves when a large tuning range is needed. A wavemeter laser

§ This method has also been used in the pioneering work of Braginsky et al.[19] and in another geometry in Paris[20] where also eroded fibre couplers and tapered fibres have been used [24].

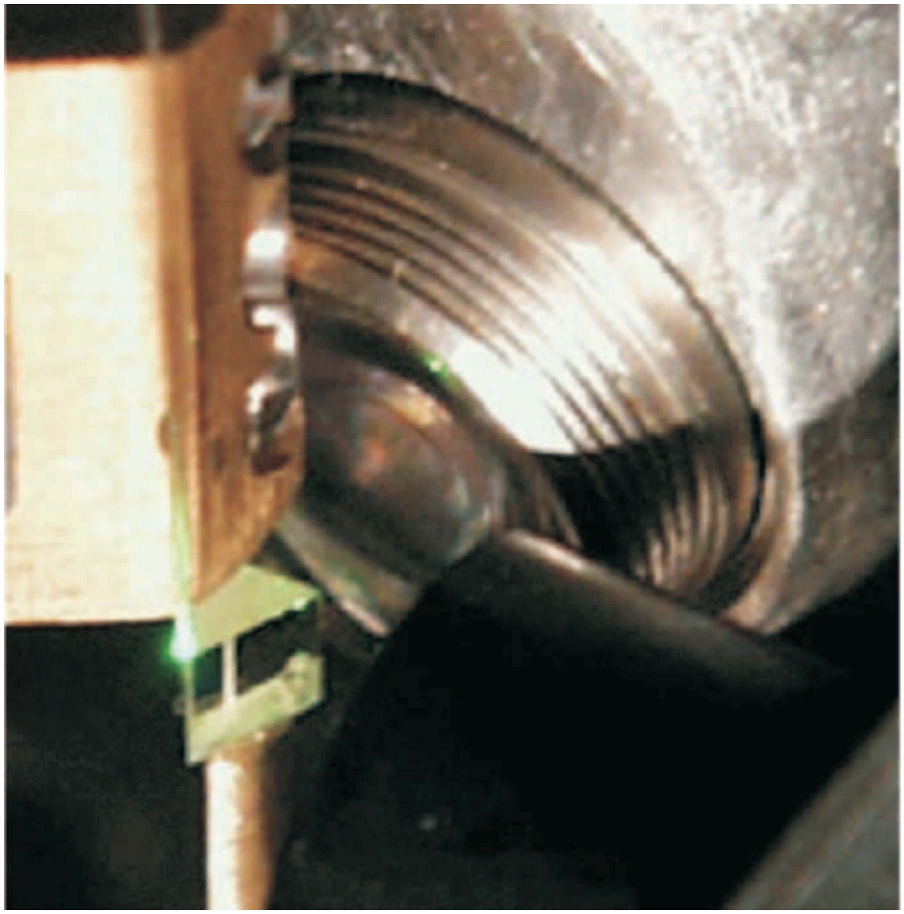

Figure 3. A photo of the central part of the experiment. The brass holder (top left of the picture) holds a single stemmed Er^{3+} doped ZBLAN sphere ($\varnothing = 140\,\mu$m). An aspherical lens (lower right side) projects the light (10 mW, 800 nm) from an optical fibre onto the prism. Part of the laser light is absorbed by the microsphere and re-emitted at 550 nm. Some of the fluorescent light exiting the sphere can be seen in the photo as a bright spot near the corner of the prism. The lens (top right side) collimates the remaining IR pump radiation and the emitted green laser light. It can thus be analysed outside of the temperature controlled central part of the experiment.

provides the absolute frequency scale with a precision of about 10^{-4} nm. A small fraction of the laser light ($\sim 3\%$) traverses a calibrated high-finesse Fabry Perot cavity. The transmission peaks of the Fabry Perot cavity are recorded together with any absorption data taken and thus give a precise relative frequency scale. The remainder of the light couples into a single mode fibre after intensity and polarization control. This fibre leads into a temperature controlled box containing the launching and collection optics as well as the microsphere with the necessary mechanical controls. A high aperture lens collimates the light exiting the fibre onto the equilateral coupling prism (SF11). The angles of incidence and the numerical aperture are calculated in advance as a function of the size of the sphere and accordingly adjusted before introducing the microsphere. The light coupled out of the sphere is collimated and analyzed outside the confinement. The

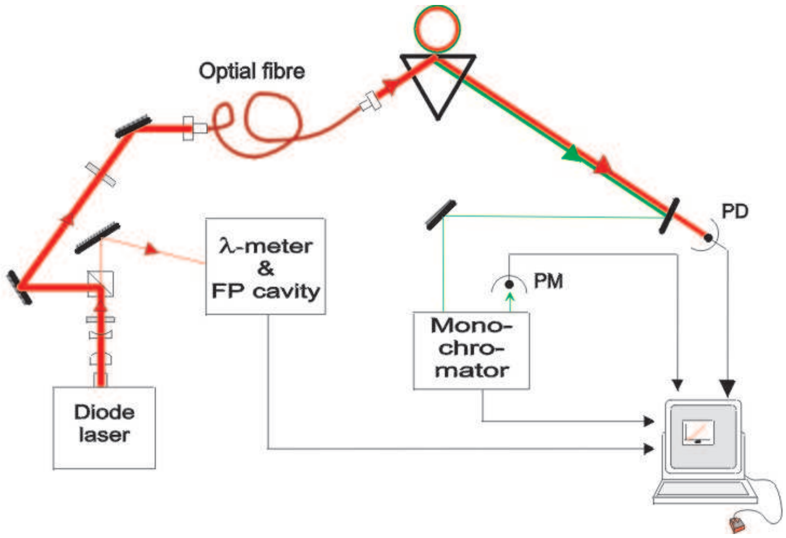

Figure 4. Approaching a high refractive index prism to the sphere (not to scale) one can frustrate the total internal reflection of the WGMs within the sphere and couple light into or out of the sphere.

microsphere itself is mounted on 3D micrometer translation stages. The gap between the sphere and the prism can be adjusted with nanometric precision using a low voltage piezostack.

3.2. Tuning Microspheres

Until recently the main default of the solid microspheres has been that the frequencies of the resonances are not tunable. The free spectral range (FSR) in small spheres is of the order of THz whilst the line width of the resonances is about 300 kHz. Therefore accidental coincidences between an atomic line and the fundamental transverse whispering gallery mode are extremely rare. We have recently demonstrated a tuning device capable of spanning up to an FSR. This opens a whole new range of experiments to solid dielectric microspheres. Now fixed dipoles can be brought into interaction with these resonators. Applications include CQED experiments with cooled atoms, or cavity-ring-down spectroscopy of environmentally important gases. Recently the first practical tuning device has been developed in our laboratory.[25].

A number of conditions have to be fulfilled in order for the tuning device to be useful: First of all it must safeguard the high quality factor and function for small spheres to take advantage of the reduced mode volume. The tuning range should be of the same order of magnitude as the free spectral range (FSR)in order to be able to tune a desired WGM into resonance with, e.g., an atomic transition or resonances in quantum dots. The device has to be exceedingly stable. A change by only 10^{-7} of the desired tuning range would already shift the WGMs by one resonant linewidth. Good access to the sphere must be safeguarded in order to be able to approach a prism from one side and the sample the sphere is to interact with from the other. Furthermore the

device should be readily producible and affordable, which is especially important for potential applications, e.g. as trace gas detectors. In many cases vacuum compatibility and/or low temperature operation would be highly desirable. Here two devices are rapidly presented which fulfils all these conditions with the first one aiming more for spectroscopic applications the other for the more demanding CQED experiments. Some detail as to the production are going to be given and some examples of level (anti-) crossings will be presented.

In principal there are two methods to tune whispering gallery modes in solid dielectric microspheres: temperature [26] and strain [27]. At first order, both affect the mode resonance through the simple relation: $\Delta\nu/\nu = -\Delta a/a - \Delta N/N$, where a is the radius of the sphere and N its refractive index. The temperature dependence of the modes is about -2.5 GHz/K. Given a free spectral range of about 1 THz for a microsphere of 60 μm diameter this can only serve as fine tuning. On the other hand silica glasses can be deformed elastically up to a few percent. One FSR tuning is equivalent to $\Delta\nu/\nu \simeq 1/l$ where l is the longitudinal quantum number. For a typical sphere this implies an equatorial deformation of 0.2% are sufficient, which can be achieved in silica.[28] The first demonstration of strain tuning used piezodriven pliers in order to *compress* the microsphere.[27] About one quarter of the sphere protruded from the device thus allowing coupling to the WGMs. For a sphere of a diameter of 160 μm tuning over 150 GHz at 800 nm has been demonstrated. However, the jaws restrict the access to the sphere and the device can not be applied to spheres smaller than about 100 μm. This precludes its use in experiments on, e.g., quantum dots (access) and thresholdless lasing in Nd doped silica (size).

A new method has been developed recently in our laboratory in which the strain is applied to the sphere by *stretching* it. [25] We are now able to produce spheres with two stems, one on each pole. The strain on the microsphere can therefore now be exerted simply by pulling on the ends of the two stems. The requirements on the symmetry are rather stringent though: upon pulling the two stems even a slight angle between the two results in very large forces between the sphere and the stems and thus to early breakage.

3.3. The Production of tunable silica microspheres

The starting material for the microspheres is a rod of synthetic silica glass. This is being heated in an oxygen-propane torch and rapidly pulled into a fibre of 20–60 μm diameter. The sphere is created again by heating part of the fibre upon which the surface tension pulls the molten material into an approximately spherical shape. An industrial 10 W CO_2-laser serves as a highly controllable, clean source of heat. The process is controlled by eye through a binocular microscope. The focusing lenses and the glass fibre itself are mounted on micrometer controlled 3D translation stages.

A lens (f = 25 mm) focuses the vertical 3 mm diameter CO_2-laser beam to a waist of about 30 μm. It thus creates a strong vertical gradient in the intensity of the infrared

radiation. The fibre hanging down is only heated near the focus. The glow of the silica due to the heating is visible in a stereo microscope and serves as an indication of the temperature of the glass. (Grey and UV filters have to be used to protect the eyes.) Close to the melting point the surface tension starts to pull the glass into a round shape. However, since the laser light comes from below this shape will cast a shadow upon itself and little radiation reaches the equator. As a consequence not a sphere but a pear shaped object is being formed. This can be corrected for by slowly moving the sphere down past the free space focus of the CO_2-laser towards the point of maximum wave front curvature. The shadow of the sphere now lies on the stem above the sphere and protects it from the heat whilst the large aperture of the incident light allows the equator efficiently to be heated. As can be seen on the left hand side of Fig.5 the result is rather symmetrical with respect to the equatorial plane. The production of such a sphere including the fibre preparation takes only about ten to twenty minutes on a well adjusted laser set up.

As mentioned above it is absolutely crucial to preserve the symmetry of revolution of the microsphere and stems. Otherwise the stems will rupture prematurely. Our production setup obeys this symmetry: The CO_2-laser beam and the fibre both are strictly vertical. However, once the melting process has started the slightest current of air will move the lower stem to one side. In order to guarantee the fibre being vertical we thus use a small weight (5–10 mg) attached to its lower end. Additionally before producing the actual sphere residual tension in the fibre, caused e.g. by imperfect mounting, is removed by annealing it with the CO_2-laser: Close to but below the melting point the residual stress relaxes on a time scale of a few seconds.

3.4. The tuning device #1

Figure 5 shows the tuning device #1. The sphere with its two stems is glued between two brass arms which can be opened and closed with fine screws and a low voltage PZT-stack. At the tips of the two arms are U shaped notches of the dimensions $0.1\times0.5\times5$ mm with a 3–5 mm gap between them. Into these the stems of the sphere are fixed using standard cyanoacrylate glue. The set screw is then tightened to remove the inevitable slack in the stems so that the PZT can exert strain on the stems and thus the sphere. Spheres with a diameter down to about $60\,\mu$m and a stem diameter of about $40\,\mu$m can be easily used in this device. Much thinner stems break too easily in the gluing and pre-tightening stage. The maximal travel of the piezostack is $7\,\mu$m which translates into an unloaded movement of about $80\,\mu$m at the fibre. This device thus allows us to stretch the fibre by about one percent which is close to the maximum elastic deformation tolerated by the silica glass and near the value needed to tune one free spectral range.

The average tuning range of the modes in the sphere has been assessed by continuously increasing the voltage at the PZT and observing the modes passing through the frequency window scanned by the diode laser. Assuming there is no strong non linearity in the tuning rate the average tuning range of the modes with respect to the

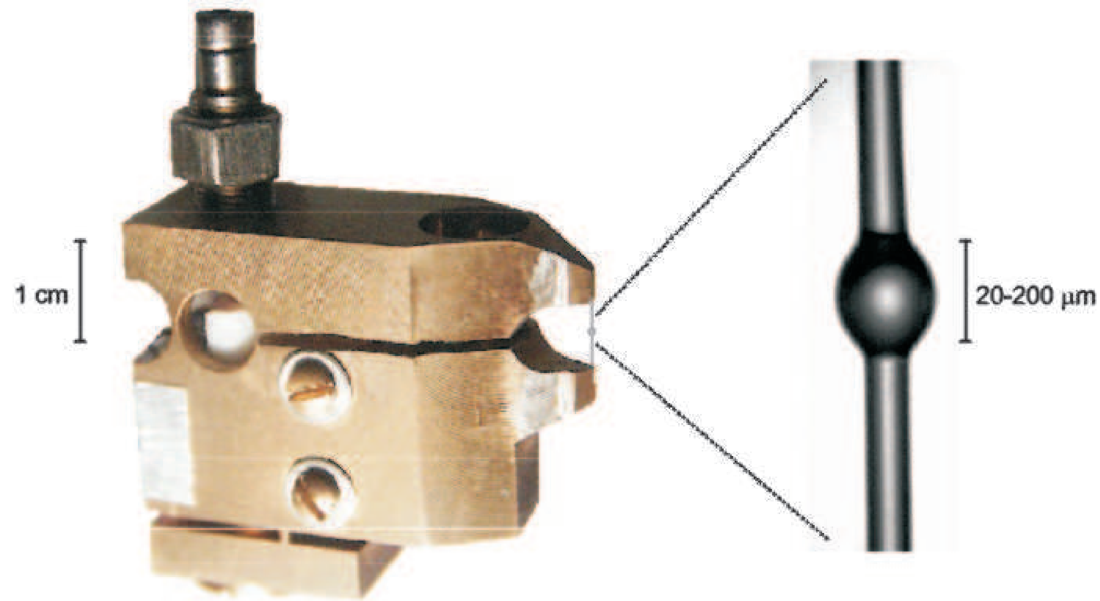

Figure 5. The first tuning device. Two brass jaws hold a double stemmed sphere of a diameter between 60 and 200 μm. The WGMs of the sphere can be tuned by stretching it using a fine screw and a low voltage PZT stack. The right hand side of the figure shows a CCD camera microscope image of a typical microsphere.

voltage applied to the PZT can thus be deduced. The resulting maximal continuous tuning range is therefore 150 GHz which is about half of an FSR for the 210 μm sphere studied here. A full FSR could not be reached mainly due to the stem being significantly thinner than the sphere. Assuming a diameter of the sphere twice as large as the one of the stem the stress on the material will be four times as large on the stem. This leads to a failure before the maximum tuning range for the sphere is reached. The tuning range of 150 GHz demonstrated here, however, already suffices since it requires on average only two attempts to find a sphere with predefined transverse and radial quantum numbers to coincide with a given frequency, e.g. of an atomic line. An analysis of the tuning shows that the major part of the tuning is due to geometric deformation of the sphere. Therefore the modes must increase in frequency with increasing strain, as can be seen in figure 6. It is therefore expected that the slope of the tuning with respect to the voltage applied on the PZT depends on the mode geometry as is apparent in figure 6. However, there is also a contribution form the birefringence introduced by the stress: TM modes tune more efficiently than TE modes. Figure 6 shows a series of scans of two resonances of opposite polarisation against the voltage applied on the PZT. Clearly the TM mode tunes more rapidly. For demonstration purposes the sphere was made from inhomogeneous material. The quality factor of the sphere was basically unaffected by this. § A Q of 5×10^8 was measured. On the other hand the coupling between certain

§ In order to improve the contrast in figure 6 the gap between the sphere and the prism was chosen to be very small. This increases the coupling between the WGMs and the prism and thus enlarges the

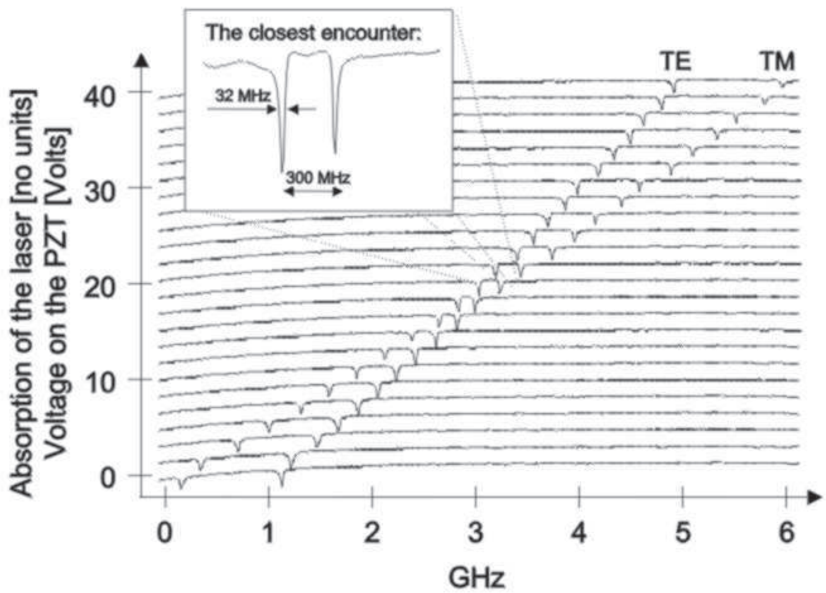

Figure 6. A series of scans of the WGM-resonances in a sphere against the voltage applied on the PZT. The horizontal axis is the frequency of diode laser. The vertical axis shows the transmission (in arbitrary units) offset by the voltage of the PZT. A dip in the transmission equates to an absorption by a whispering gallery mode. For the sake of clearness the scans have been offset proportionally to the voltage applied to the PZT. The insert shows the closest point of the avoided crossing between the TE and TM modes. The intrinsic quality factor of the sphere was $Q = 5 \times 10^8$.(see footnote §)

modes of opposite polarisation was greatly enhanced resulting in an avoided crossing of 300 MHz (see insert in figure 6). In 'perfect' spheres the coupling between modes is of the order of the coupling via backscattering, i.e. a few hundred kilohertz.

The long term stability of the modes is excellent. Over a number of days the modes drifted less than 10 GHz. On a shorter time scale the stability was limited by fluctuations in the background temperature. In *all* the spheres produced by this method and tested here we measured a quality factor of the order of 10^9. These are amongst the highest at this wavelength. Figure 7 shows one such measurement. The linewidth of 370 kHz measured at 800 nm corresponds to a Q in excess of 10^9. The splitting of 539 kHz between the peaks results from a coupling of modes of opposite sense of rotation due to back-scattering of the light by defects in the silica or residual surface roughness [29]. As expected, the splitting remains constant even if the frequencies of the modes are tuned. The quality factor can be preserved under atmospheric conditions for a few days. A reduction in the Q is usually sudden and can often be traced back to a microscopic dust particle settling in the vicinity of the WGM.

This first device can tune WGMs of the microspheres of down to a diameter of $60\,\mu$m by about half of an FSR whilst preserving very good access and maintaining

modes in figure 6 beyond their intrinsic line width.

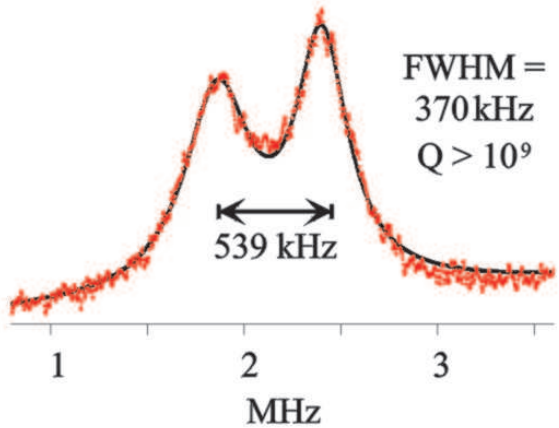

Figure 7. The intensity of the light absorbed by the sphere. The black line is a fit of two Lorentzian lines to the data. The lines are 370 kHz wide equating to a quality factor in excess of 10^9. The doublet originates in a coupling of counter-propagating modes due to backscattering

their high a quality factor of more than 10^9.

3.5. The tuning device #2

For cavity quantum electronics experiments it is highly desirable to use very small spheres in ultra high vacuum conditions. This is difficult to realise with the first design due to the minimum size of the spheres of about 60 μm. The second tuning device we developed addresses this concerns. It can be seen in figure 8. It consists of a U shaped base which can be opened and closed with a screw and a vacuum compatible low voltage PZT stack. Rods of pure silica are fixed onto the jaws of the device and subsequently bent in an oxygen-propane flame to meet at the centre in front of the device. The tips are then ground to the shape of a pyramids with a tip to tip distance of about 400 μm.

Next the CO_2-laser is used to weld a short piece of silica fibre across the gap between the tips of the pyramids. The inevitable residual stress is removed by again gently heating the material with the CO_2-laser. The fibre is then placed into the focus of two exactly counter-propagating laser beams (lenses $f = 25.4$ cm). The material is carefully heated whilst the tension on the PZT is continuously increased. This stretches the material at the focus of the laser. The procedure is repeated some tens of micrometers below. The result is a double neck in the fibre. The centre between the two indentations is then heated strongly and the voltage slowly relaxed. The surface tension pulls the material thus provided into a good approximation of a sphere. (See insert in figure 8) The relatively thick stem assures that much of the deformation results in strain on the sphere and does not just stretch the stems. The indentations on either side of the sphere reduce its ellipticity.

The second device was studied with a narrow linewidth tunable DBR diode laser (Yokogawa YL78XNL). By scanning simultaneously the laser current and the injection

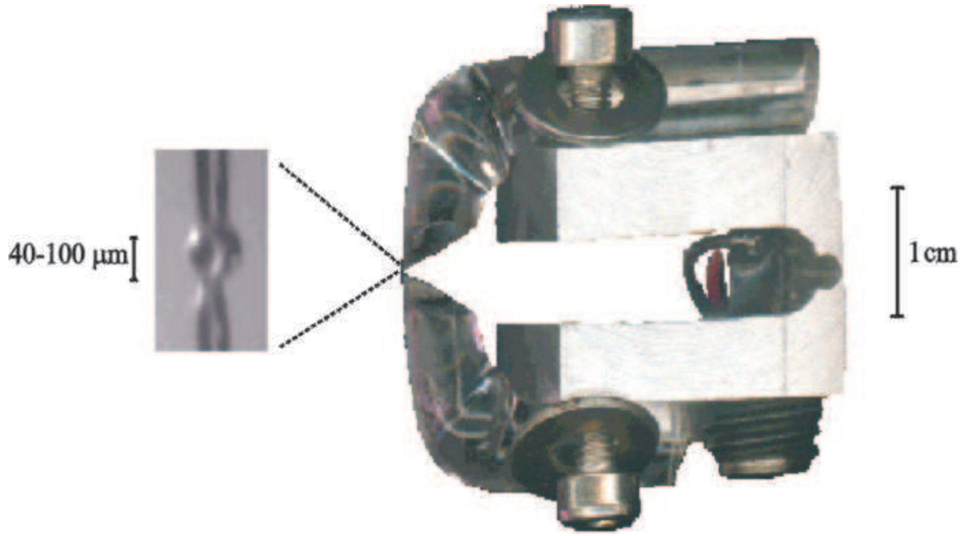

Figure 8. The second tuning device. On the left of the device can be seen an optical microscope image of the double stemmed 'sphere'

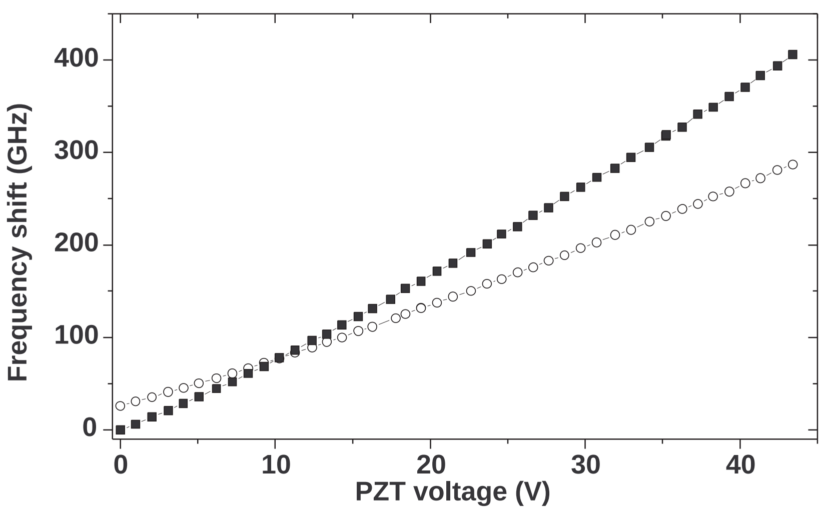

Figure 9. Frequency shift for a TM (▪) and a TE (○) mode followed continuously over the maximum tuning range.

current into the Bragg grating this laser can be tuned continuously by up to 1 nm. Its linewidth is about 1 MHz. The tuning of the WGMs could therefore be observed directly over its maximum range. Figure 9 shows the tuning of two WGMs in the sphere against the voltage applied on the PZT. The frequency of the resonance has been changed by 405 GHz before the device failed due to a fracture at the joint between the fibre and the mount. Half of an FSR of the sphere has thus been scanned. Again, as expected, the TE mode moved more slowly with the PZT voltage than the TM mode.

The Q factor was lower than 10^9, the value measured with device 1. This is probably due to some contamination of the sphere's surface, possibly due to the deposition of

a small amount of crystallized silica. This will be avoided in the future by a slight modification in the fabrication process.

The stability of the frequency of the modes is as mentioned of particular concern to any future experiments with tunable microspheres. The tuning was found to be perfectly reversible: On the time scale of up to a week no drift of the modes, e.g. due to plastic deformation of the sphere, could be observed.

The second device can tune the WGMs by about one half of an FSR. Good access is still granted. Spheres of a diameter down to about 30 μm can be used.

3.6. A comparison between the two devices

The two different models of tuning devices presented above serve quite different applications. The first one is clearly more suitable for applications such as spectroscopy or spectral filtering. It is very simple to produce: A new resonator can readily be made and coupled to a laser in less than one hour. It might even be possible to mechanise such a production by adapting well established pipette-pulling technology. The tuning device affords excellent access, good robustness, and ease of use. Its main limitations are its minimum sphere diameter of 60 μm and the relatively long stems necessary to fix the sphere to the jaws of the device.

The second design has a potentially larger tuning range. It permits smaller spheres to be used. Tuning of spheres down to less than 40 μm has been demonstrated. It has excellent vacuum compatibility and is more compact thus limiting the cost of vacuum system. Its main drawback compared to the first device lies in the more complicated production procedures requiring considerable more skill and time. The second device is being used in ongoing CQED experiments in our group.

4. Conclusion

A more detailed analysis has been reported of two novel devices for microspheres which finally allows these extraordinary resonators to be tuned into resonance with atomic and molecular transitions. This opens the way toward a whole new range of experiments in CQED and ultra sensitive spectroscopy. It has now become feasible to couple ultra cold atoms or quantum-dots to the microspheres. The tunable microspheres will serve as affordable 'super' cavities for the detection of trace gases, e.g. by cavity ring down spectroscopy.

Acknowledgments

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Bibliography

[1] A. J. Campillo, J. D. Eversole, and H. B. Lin, "Cavity quantum electrodynamics enhancement of stimulated emission in microdroplets," Phys.Rev.Lett. **67,** 437–440 (1991).

[2] F. Treussart, J. Hare, L. Collot, V. Lefèvre, D. S. Weiss, V. Sandoghdar, J. M. Raimond, and S. Haroche, "Quantized atom-field force at the surface of a microsphere," Optics Letters **19,** 1651–1653 (1994).

[3] S. Schiller and R. L. Byer, "High-resolution spectroscopy of whispering gallery modes in large dielectric spheres," Optics Letters **16,** 1138–1140 (1991).

[4] V. S. Ilchenko and M. L. Gorodetsky, "Thermal nonlinear effects in optical whispering gallery microresonators," Laser Physics **2,** 1004–1009 (1992).

[5] H.-B. Lin and A. J. Campillo, "CW nonlinear optics in droplets microcavities displaying enhanced gain," Phys.Rev.Lett. **73,** 2440–2443 (1994).

[6] H. Heitmann, Y. Kadota, T. Kawakami, , and Y. Yamamoto, "Single Transverse-Mode Microcavity Laser With Ultralow Threshold," Japanese Journal of Applied Physics Part 2-Letters **32-8b,** L1141–L1143 (1993).

[7] W. von Klitzing, E. Jahier, R. Long, F. Lissillour, V. LefevreSeguin, J. Hare, J. M. Raimond, and S. Haroche, "Very low threshold lasing in Er^{3+} doped ZBLAN microsphere," Electronics Letters **35,** 1745–1746 (1999).

[8] F. D. Martini, G. Innocenti, G. R. Jacobivitz, and P. Mataloni, "Anomalous spontaneous emission time in a microscopic optical cavity," Phys.Rev.Lett. **59,** 2955–2958 (1987).

[9] A. J. Horowicz, H. Heitmann, Y. Kadota, and Y. Yamamoto, "GaAs microcavity quantum-well laser with enhanced coupling of spontaneous emission to the lasing mode," Appl Phys Lett **61,** 393–395 (1992).

[10] P. W. H. Pinkse, T. Fischer, P. Maunz, and G. Rempe, "Trapping an atom with single photons," Nature **404,** 365–368 (2000).

[11] C. J. Hood, T. W. Lynn, A. C. Doherty, A. S. Parkins, and H. J. Kimble, "The Atom-Cavity Microscope: Single Atoms Bound in Orbit by Single Photons," Science **287,** 1447–1453 (2000).

[12] R. J. Thompson, G. Rempe, and H. J. Kimble, "Observation of normal-mode splitting for an atom in an optical cavity," Phys.Rev.Lett. **68,** 1132 (1992).

[13] K. An, J. J. Childs, R. R. Dasari, and M. S. Feld, "Microlaser: a laser with one atom in an optical resonator," Phys.Rev.Lett. **73,** 3375 (1994).

[14] P. W. H. Pinkse, T. Fischer, P. Maunz, and G. Rempe, "Trapping an Atom With Single Photons," Nature **404,** 365–368 (2000).

[15] N. A. Logan, "Survey of Somme Early Studies of the Scattering of Plane Waves by a Sphere," Proc IEEE **53,** 773–785 (1965).

[16] *Optical processes in microcavities*, Vol. 3 of *Advanced Series in Applied Physics*, R. K. Chang and A. J. Campillo, eds., (World Scientific, 1996).

[17] S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, "Whispering-gallery mode microdisk lasers," Appl Phys Lett **60,** 289–291 (1992).

[18] J. M. Gerard, B. Sermage, B. Gayral, B. Legrand, E. Costard, , and V. T. Mieg, "Enhanced Spontaneous Emission by Quantum Boxes in a Monolithic Optical Microcavity," Phys.Rev.Lett. **81,** 1110–1113 (1998).

[19] V. B. Braginsky, M. L. Gorodetsky, and V. S. Ilchenko, "Quality-factor and non-linear properties of optical whispering-gallery modes," Phys Lett A **137,** 393–397 (1989).

[20] L. Collot, V. Lefèvre-Seguin, M. Brune, J. M. Raimond, and S. Haroche, "Very high-Q whispering-gallery mode resonances observed on fused silica microspheres," Euro Phys Lett **23,** 327–334 (1993).

[21] M. L. Gorodetsky, A. A. Savchenkov, and V. S. Ilchenko, "Ultimate Q of optical microsphere resonators," Optics Letters **21,** 453–455 (1996).

[22] P. W. Barber and R. K. Chang, *Optical Effects Associated With Small Particles*, Vol. 1 of *Advanced*

series in applied physics (World Scientific, 1988).

[23] L. G. Guimaraes and H. M. Nussenzveig, “Uniform Approximation to Mie Resonances,” Journal of Modern Optics **41,** 625–647 (1994).

[24] N. Dubreuil, J. C. Knight, D. K. Leventhal, V. Sandoghdar, J. Hare, and V. Lefèvre, “Eroded monomode optical fiber for excitation in fused-silica microspheres,” Optics Letters **20,** 813–815 (1995).

[25] W. von Klitzing, R. Long, S. Ilchenko, J. Hare, and V. Lefèvre-Seguin, “Frequency tuning of the whispering gallery modes of silica microspheres for CQED and spectroscopy,” e-print quant-ph/0008010 pp. 1–4 (2000).

[26] D. W. Vernooy, A. Furusawa, N. P. Georgiades, V. S. Ilchenko, and H. J. Kimble, “Cavity QED With High-Q Whispering Gallery Modes,” Physical Review A **57-4,** R2293–R2296 (1998).

[27] V. S. Ilchenko, P. S. Volikov, V. L. Velichansky, F. Treussart, V. Lefèvre-Seguin, J. M. Raimond, and S. Haroche, “Strain-tunable high-Q optical microsphere resonator,” Optics Communications **145,** 86–90 (1998).

[28] A. L. Huston and J. D. Eversole, “Strain-sensitive elastic scattering from cylinders,” Optics Letters **18,** 1104 (1993).

[29] D. S. Weiss, V. Sandoghdar, J. Hare, V. Lefèvre-Seguin, J. M. Raimond, and S. Haroche, “Splitting of high-Q mie modes induced by light backscattering in silica microspheres,” Optics Letters **20,** 1835–1837 (1995).